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Fast Dispersive Beam Deflectors and Modulators

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Abstract—A new method for one-dimensional light scanning is proposed. It is based on the use of ordinary dispersive optical components like prisms, gratings, etc. By electrooptic tuning of the output wavelength of broad-band lasers, fast scanners (up to 10 gigapixels/s) can be constructed. Deflection angles and numbers of pixels are derived for the prism, grating, Fabry-Perot etalon, and phase-matched frequency doubler crystal. Experimental results on the frequency doubler device are presented.

INTRODUCTION

THE existence of broad-band tunable lasers such as dye lasers or the alexandrite laser implies that it is possible to construct fast line scanners or modulators by means of a dispersive element and a tuning element activated by electric or magnetic fields.

Telle and Tang [1] demonstrated an electrooptic tuning element in 1974. Later, a similar device became commercially available with tuning rates up to 80 nm/kV (± 7 , 5 kV) and maximum frequencies up to 5 MHz [2]. Using such a tuning element in a dye laser or an alexandrite laser together with a dispersive element it is possible to obtain scanning rates up to the order of 10^{10} pixels/s as discussed below. The scanning

takes place in one dimension. Another type of deflector must be added in order to obtain two-dimensional scanning.

In the following we shall discuss four dispersive components which can be applied as deflectors or modulators: the prism, the grating, the Fabry-Perot etalon, and the phase-matched frequency doubler. Three quantities are important when specifying these kinds of deflectors or modulators, the angular deflection per unit wavelength $d\theta/d\lambda$, the number of pixels (picture elements) per unit wavelength $dN/d\lambda$, and the total number of pixels N obtainable with the system. From these it is easy to find the angular deflection $\Delta\theta$ and the wavelength increase $\Delta\lambda$ per pixel which are more relevant for modulators.

The resolving power A of a dispersive element is given by

$$A = \frac{\lambda}{\Delta\lambda} \quad (1)$$

where $\Delta\lambda$ is the wavelength interval just resolved by the element. Hence, the wavelength increase per pixel is

$$\Delta\lambda = \frac{\lambda}{A} \quad (2)$$

and the number of pixels per unit wavelength is

$$\frac{dN}{d\lambda} = \frac{1}{\Delta\lambda} = \frac{A}{\lambda} \quad (3)$$

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The total number of pixels for the system is then

$$N = \frac{dN}{d\lambda} (\lambda_2 - \lambda_1) \quad (4)$$

where λ_1 and λ_2 are the tuning limits of the laser.

A prism has an angular deflection per unit wavelength given by [3]

$$\frac{d\theta}{d\lambda} = \frac{b}{h} \frac{dn}{d\lambda} \quad (5)$$

where b and h are base and height of the prism and n is the refractive index. The resolution of a prism is given by [4]

$$A = b \frac{dn}{d\lambda} \quad (6)$$

if the prism is completely filled with light. Hence, according to (3)

$$\frac{dN}{d\lambda} = \frac{b}{\lambda} \frac{dn}{d\lambda} \quad (7)$$

A grating has an angular deflection per unit wavelength given by [5]

$$\frac{d\theta}{d\lambda} = \left(\left(\frac{d}{m} \right)^2 - \left(\lambda + \left(\frac{d}{m} \right) \sin \theta_0 \right)^2 \right)^{-1/2} \quad (8)$$

where d is the spacing between the grooves, m is the order, and θ_0 is the angle of incidence. The resolution of the grating is [5]

$$A = m \frac{D}{d} \quad (9)$$

where D is the diameter of the laser beam at the grating, implying

$$\frac{dN}{d\lambda} = \frac{m}{d} \frac{D}{\lambda} \quad (10)$$

A Fabry-Perot etalon has an angular deflection per unit wavelength given by [6]

$$\frac{d\theta}{d\lambda} = - \frac{\cot \theta}{\lambda} \quad (11)$$

which increases strongly for fringes close to the axis. Close to $\theta = 0$ (11) is not useful. Here the variation in θ required to move a passband by one order is approximately [6]

$$\Delta\theta \simeq \left(\frac{\lambda}{nd} \right)^{1/2} \quad (12)$$

where nd is the optical length of the etalon. The corresponding wavelength change (free spectral range) is

$$\Delta\lambda = \frac{\lambda^2}{2nd} \quad (13)$$

yielding an approximate deflection rate close to $\theta = 0$

$$\frac{d\theta}{d\lambda} = 2 \left(\frac{nd}{\lambda^3} \right)^{1/2} \quad (14)$$

The resolution at $\theta = 0$ is given by [6]

$$A = \frac{2ndF}{\lambda} \quad (15)$$

where F is the finesse of the etalon.

The number of pixels per unit wavelength is then

$$\frac{dN}{d\lambda} = \frac{2ndF}{\lambda^2} \quad (16)$$

However, the etalon is only useful within one free spectral range (13). The total number of pixels is then

$$N = \frac{dN}{d\lambda} \Delta\lambda = F \quad (17)$$

which is usually of the order of 100. Similarly, the total useful deflection angle is given by (12).

The last dispersive element to be discussed is the phase-matched frequency doubler. If the fundamental beam is well focused inside a frequency doubler crystal there exists a solid angle within which sufficient fundamental beam power is available. The second harmonic beam will then form along the direction where phase matching occurs within a cone with an angle of apex given by [7]

$$\Delta\theta = \frac{0.44\lambda/l}{\partial(n_1 - n_2)/\partial\theta} \quad (18)$$

where l is the crystal length and

$$\frac{\partial(n_1 - n_2)}{\partial\theta} \simeq (n_2^o - n_2^e) \sin 2\theta_0 \quad (19)$$

n_2^o and n_2^e are refractive indexes of ordinary and extraordinary waves at the second harmonic frequency and θ_0 is the phase-match angle (between optic axis and propagation direction). Only the wavelength interval $\Delta\lambda$ contributes to the second harmonic beam [7]

$$\Delta\lambda = \frac{0.44\lambda/l}{\partial n_1/\partial\lambda - \frac{1}{2} \partial n_2/\partial\lambda_2} \quad (20)$$

where

$$\frac{\partial n_1}{\partial\lambda} - \frac{1}{2} \frac{\partial n_2}{\partial\lambda_2} = \frac{\partial n_1}{\partial\lambda} - \frac{1}{2} \left(\cos^2 \theta_0 \frac{\partial n_2^o}{\partial\lambda} + \sin^2 \theta_0 \frac{\partial n_2^e}{\partial\lambda} \right) \quad (21)$$

and n_1 is the refractive index for the fundamental beam.

If the wavelength of the fundamental beam is changed a little, the direction of phase match is also changed so that

$$\frac{d\theta}{d\lambda} = \frac{\partial n_1/\partial\lambda - \frac{1}{2} \partial n_2/\partial\lambda_2}{\partial(n_1 - n_2)/\partial\theta} \quad (22)$$

The second harmonic beam is thus deflected according to (22) by varying the wavelength of the fundamental beam. Since two beams can just be resolved when they are $\frac{1}{2} \Delta\theta$ or $\frac{1}{2} \Delta\lambda$ apart, the number of pixels per unit wavelength is

TABLE I

PROPERTIES OF DIFFERENT DISPERSIVE BEAM DEFLECTORS COMPUTED FROM (5)-(26). $d\theta/d\lambda$ AND $dN/d\lambda$ ARE THE DEFLECTION ANGLE AND NUMBER OF PIXELS PER UNIT WAVELENGTH, N IS THE TOTAL NUMBER OF PIXELS DETERMINED BY THE TUNING RANGE (120 nm).

$\Delta\theta$ AND $\Delta\lambda$ ARE ANGLE AND WAVELENGTH INTERVALS PER PIXEL. THE PARAMETERS USED ARE FOR THE PRISM: $b = 50$ mm, $h = 43.3$ mm, $dn/d\lambda = 4 \cdot 10^{-5}$ nm $^{-1}$; FOR THE GRATING: $d = 1$ μ m, $m = 1$, $\theta_o = 0$, $D = 20$ mm; FOR THE FABRY-PEROT: $nd = 50$ mm, $F = 100$; AND FOR THE FREQUENCY DOUBLER (LiIO $_3$): $l = 14$ mm, $\delta = 5.3$ mm, $\theta_o = 45^\circ$, $n_1 = n_2 = 1.870$, $\partial n_1/\partial\lambda = -0.0683$ μ m $^{-1}$, $\partial n_2^2/\partial\lambda = -0.566$ μ m $^{-1}$, $\partial n_2^2/\partial\lambda = -0.529$ μ m $^{-1}$, $n_2^2 = 1.96$, $n_2^2 = 1.79$. (WITH $\delta = 5.3$ mm (23) AND (26) YIELD THE SAME RESULTS.)

EVERYWHERE THE WAVELENGTH 750 nm HAS BEEN USED, A TUNING RANGE OF 120 nm HAS BEEN ASSUMED CORRESPONDING TO THE PARAMETERS OF THE ALEXANDRITE LASER.

	$\frac{d\theta}{d\lambda}$	$\frac{dN}{d\lambda}$	N	$\Delta\theta$	$\Delta\lambda$
	mrad/nm	pixels/nm	pixels	mrad	nm
PRISM	0.05	3.2	380	0.016	0.31
GRATING	1.5	27	3200	0.056	0.038
FABRY-PEROT	890	2.5×10^4	100	0.036	4.0×10^{-5}
FREQ. DOUBLER	1.2	17	2000	0.071	0.059

$$\frac{dN}{d\lambda} = \frac{1}{\frac{1}{2}\Delta\lambda} = \frac{\partial n_1/\partial\lambda - \frac{1}{2}\partial n_2/\partial\lambda}{0.22\lambda/l} \quad (23)$$

However, diffraction effects have not been considered here. The cone formed by the focused fundamental beam results in a beam diameter

$$\delta = \frac{D}{f} \frac{l}{n_1} \quad (24)$$

at the output face of the doubler crystal. Here D is the diameter of the input laser beam, f is the focal length of the focusing lens, l is the crystal length, and n_1 is the refractive index for the fundamental beam. Since the second harmonic beam is formed within the diameter δ , the diffraction angle is

$$\Delta\theta_D = \frac{\lambda_2}{\delta} = \frac{f\lambda_2 n_1}{Dl} \quad (25)$$

where λ_2 is the wavelength of the second harmonic light. The number of pixels per unit wavelength caused by the diffraction limit is then

$$\left(\frac{dN}{d\lambda}\right)_D = \frac{d\theta}{d\lambda} \frac{1}{\Delta\theta_D} = \frac{Dl}{f\lambda_2 n_1} \frac{d\theta}{d\lambda} \quad (26)$$

In a practical design the parameters should be adjusted so that (23) and (26) yield the same number of pixels.

In Table I actual numbers have been inserted into the expressions just derived. The table has been computed using the wavelength 750 nm and a tuning range of 120 nm corresponding to the parameters of the alexandrite laser. It is seen that the prism has a small angular dispersion, but a reasonable number of pixels. The grating yields a good angular deflection and a large number of pixels which can easily be increased by using larger gratings (larger spot sizes at the grating). The Fabry-Perot etalon has a very large angular dispersion, but it is only useful within one free spectral range of 0.004 nm (3 GHz) for the example shown in Table I where it yields a total deflection of 3.6 mrad with about 100 pixels

(number of pixels equals the finesse). Hence, the Fabry-Perot deflector can be applied in case of narrow bandwidth lasers like the usual gas lasers. The resonators of these must then be changed to include a tuning element which makes it possible to scan the output laser wavelength across the gain curve.

The phase-matched LiIO $_3$ frequency doubler device shown in Table I has a performance similar to the grating. It has the advantage of being more compact and its output wavelength is UV where photosensitive materials usually are best when used with the alexandrite laser. Furthermore, the laser linewidth need not be so narrow as, for example, when the grating deflector is applied. We have investigated experimentally the LiIO $_3$ deflector used as an example in Table I. We applied a fundamental beam with $\lambda = 750$ nm from a CW dye laser (with Oxazine dye) pumped by a krypton laser. The beam was focused with a 12.6 mm focal length lens into the LiIO $_3$ crystal which was cut in a direction 45° from the optic axis yielding type I phase matching for 750 nm. The apex angle of the second harmonic beam was measured to be about 1 mrad (full angle measured outside the crystal). This is about a factor of 4 more than the 0.26 mrad ($0.071 \times 2 \times 1.87$) mrad expected from Table I. However, δ [in (24)] was about 0.5 mm in the present experiment implying a full diffraction angle of 1.5 mrad. We measured a deflection rate of 4.3 mrad/nm (measured outside the crystal). The internal deflection rate is a factor of $n = 1.87$ less than the external one or 2.3 mrad/nm which is somewhat larger than predicted in Table I from (22). The total scan width obtained with the 12.6 mm focal length lens was 4 degrees (measured outside the crystal). This value agrees well with the focusing cone obtained with the 12.6 mm lens and input beam diameter of 1 mm. The number of pixels in this setup was then about 140, but can be increased by increasing the solid angle of the focusing cone of the fundamental beam.

As shown in Table I, a few thousand pixels can be obtained from both grating and doubler deflectors. With a maximum scan frequency of 5 MHz [2] scan rates up to 10 gigapixels/s

should be possible, making these deflectors considerably faster than usual acoustooptic deflectors which have maximum speeds of 20–30 megapixels/s [8]. A typical acoustooptic deflector scans some hundred pixels with a total deflection of the order of 10 mrad. Hence, some of the dispersive deflectors shown in Table I have better performance than the ordinary acoustooptic deflector.

CONCLUSION

It has been shown that it is possible to construct fast beam deflectors based on usual dispersive optical components by means of electrooptic tuning of broad-band lasers. Scans with several thousand pixels, about 10 degrees of deflection and with scanning rates up to 10 gigapixels/s can be obtained.

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Parametric Amplification and Frequency Conversion in Optical Fibers

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(Invited Paper)

Abstract—We find that the parametric four-photon gain for light pulses decreases for fibers longer than a characteristic length. This length is related to the common experimental observation that stimulated parametric emission is usually prominent only in short fibers while in long fibers stimulated Raman scattering dominates. Despite the fact that the actual process involves an intensity dependent bandwidth and broadening of the pump linewidth from self-phase modulation, it is possible to develop a simple expression for the characteristic length which requires only the initial pump linewidth and the low-power parametric bandwidth. This bandwidth can often be estimated from the pump wavelength and the measured frequency shift between the pump and the generated waves. Expressions for gain and amplification are derived from coupled wave equations and in the Appendixes it is shown that these are of the same form as the planewave equations, but modified by coupling coefficients called overlap integrals.

I. INTRODUCTION

A WIDE variety of nonlinear optical effects have been observed using optical fibers as the nonlinear medium. Stimulated Raman scattering and four-photon parametric mixing can be used to convert the input light into light at one or more different frequencies [1]. In multimode fibers,

both effects usually occur simultaneously although this need not necessarily be the case. In comparison with Raman frequency conversion, parametric frequency conversion is advantageous in that frequency up-conversion is possible as well as down-conversion, and the range of frequency shifts is broader. The same advantages apply when both processes are viewed as a means for amplifying light. A primary aim of this paper is to describe the circumstances which favor parametric output as opposed to Raman output. In particular, we treat the case of pulsed input light although much of the formalism is also applicable to the CW case.

The gain coefficient for four-photon parametric amplification is generally larger than that for stimulated Raman amplification. Consequently, the parametric output might be expected to always dominate over the Raman output. Using pulsed lasers, it has been observed experimentally that this is only true for fibers shorter than some characteristic length which we denote l_c . For fibers longer than l_c the stimulated Raman output dominates. In this paper we show how l_c can be evaluated and understood in terms of the frequency bandwidth of the parametric gain and self-phase modulation of the pulsed input light. We will only treat situations in which the shift between the frequencies of the generated light and the